Exclusive meson production at COMPASS

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Introduction

COMPASS experiment

Transverse target spin asymmetries for incoherent exclusive $\rho^0$ and $\omega$ production

Projections for COMPASS-II

Summary and outlook
GPD formalism

**HJard Exclusive Meson Production**
\( \gamma^* p \to V p' \)

**Chiral-even GPDs**
- helicity of parton unchanged
  - \( H^{g,g}(x,\xi,t) \)
  - \( \tilde{H}^{g,g}(x,\xi,t) \)
  - \( E^{q,g}(x,\xi,t) \)
  - \( \tilde{E}^{q,g}(x,\xi,t) \)

**Chiral-odd GPDs**
- helicity of parton changed (not probed by DVCS)
  - \( H^q_T(x,\xi,t) \)
  - \( \tilde{H}^q_T(x,\xi,t) \)
  - \( E^q_T(x,\xi,t) \)
  - \( \tilde{E}^q_T(x,\xi,t) \)

**Flavour separation for GPDs**
- example:
  - \( E_{\rho^+} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u + \frac{1}{3} E^d + \frac{3}{8} E^g \right) \)
  - \( E_{\omega} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u - \frac{1}{3} E^d + \frac{1}{8} E^g \right) \)
  - \( E_{\phi} = -\frac{1}{3} E^s - \frac{1}{8} E^g \)

- contribution from gluons at the same order of \( \alpha_s \) as from quarks

large \( Q^2 \) and \( W, -t/Q^2 << 1 \)

factorization strictly proven only for longitudinal \( \gamma^* \)
GPD formalism – highlights

Nucleon tomography:
3D parton distribution function:

\[ q(x, b) = (2\pi)^{-2} \int d^2 \Delta e^{-ib \cdot \Delta} H^q(x, 0, t = -\Delta^2) \]

where:

\( b \): impact parameter

Ji’s sum rule (access to total angular momentum):

\[ \int_{-1}^{1} dx \, x [H^q(x, \xi, 0) + E^q(x, \xi, 0)] = 2J^q \]

Transversity:

\[ H_T^q(x, 0, 0) = h_1^q(x) \]
Cross section formula for exclusive meson production

\[
\frac{\alpha_{em}}{8\pi^3} \left[ \frac{y^2}{1 - \varepsilon} - \frac{1 - x_B}{x_B} \frac{1}{Q^2} \right]^{-1} \frac{d\sigma}{dx_B dQ^2 d\phi d\phi_S} = \frac{1}{2} (\sigma_{++} + \sigma_{--}) + \varepsilon \sigma_{00}^{++} - \varepsilon \cos(2\phi) \text{Re} \sigma_{00}^{++} - \sqrt{\varepsilon(1 + \varepsilon)} \cos \phi \text{Re} (\sigma_{++}^{+} + \sigma_{--}^{-}) \\
- P_\ell \sqrt{\varepsilon(1 - \varepsilon)} \sin \phi \text{Im} (\sigma_{++}^{+} + \sigma_{--}^{-}) \\
- S_L \left[ \varepsilon \sin(2\phi) \text{Im} \sigma_{++}^{++} + \sqrt{\varepsilon(1 + \varepsilon)} \sin \phi \text{Im} (\sigma_{00}^{++} - \sigma_{--}^{-}) \right] \\
+ S_L P_\ell \left[ \sqrt{1 - \varepsilon^2} \frac{1}{2} (\sigma_{++}^{++} - \sigma_{--}^{-}) - \sqrt{\varepsilon(1 - \varepsilon)} \cos \phi \text{Re} (\sigma_{00}^{++} - \sigma_{--}^{-}) \right] \\
- S_T \left[ \sin(\phi - \phi_S) \text{Im} (\sigma_{++}^{++} + \varepsilon \sigma_{00}^{++}) + \frac{\varepsilon}{2} \sin(\phi + \phi_S) \text{Im} \sigma_{++}^{++} + \frac{\varepsilon}{2} \sin(3\phi - \phi_S) \text{Im} \sigma_{++}^{++} \\
+ \sqrt{\varepsilon(1 + \varepsilon)} \sin \phi_S \text{Im} \sigma_{++}^{++} + \sqrt{\varepsilon(1 + \varepsilon)} \sin(2\phi - \phi_S) \text{Im} \sigma_{++}^{++} \right] \\
+ S_T P_\ell \left[ \sqrt{1 - \varepsilon^2} \cos(\phi - \phi_S) \text{Re} \sigma_{++}^{++} \\
- \sqrt{\varepsilon(1 - \varepsilon)} \cos \phi_S \text{Re} \sigma_{00}^{++} - \sqrt{\varepsilon(1 - \varepsilon)} \cos (2\phi - \phi_S) \text{Re} \sigma_{00}^{++} \right].
\]

\( \sigma_{mn}^{ij} \): helicity-dependent photoabsorption cross sections and interference terms

\[
\sigma_{mn}^{ij}(x_B, Q^2, t) \propto \sum (M_m^i)^* M_n^j
\]

\( M_m^i \): amplitude for subprocess \( \gamma^* p \rightarrow V p' \) with photon helicity \( m \) and target proton helicity \( i \)

\[
\varepsilon = \frac{1 - \gamma - \frac{1}{4} y^2 y^2}{1 - \gamma + \frac{1}{2} y^2 + \frac{1}{4} y^2},
\]

\[
\gamma = 2x_B M_p / Q
\]
Access to GPDs through exclusive meson production

5 transverse target spin asymmetries and 3 transverse target double spin asymmetries

\[
A_{UT}^{\sin \phi - \phi_s} = - \frac{\text{Im} (\sigma_{++}^+ + \epsilon \sigma_{00}^+)}{\sigma_0}
\]

\[
A_{UT}^{\sin 2\phi - \phi_s} = - \frac{\text{Im} \sigma_{00}^+}{\sigma_0}
\]

\[
A_{UT}^{\sin \phi_s} = - \frac{\text{Im} \sigma_{00}^+}{\sigma_0}
\]

\[
A_{UT}^{\sin 3\phi - \phi_s} = - \frac{\text{Im} \sigma_{00}^+}{\sigma_0}
\]

\[
A_{LT}^{\cos \phi - \phi_s} = \frac{\text{Re} \sigma_{++}^+}{\sigma_0}
\]

\[
A_{LT}^{\cos 2\phi - \phi_s} = - \frac{\text{Re} \sigma_{00}^-}{\sigma_0}
\]

\[
A_{LT}^{\cos \phi_s} = - \frac{\text{Re} \sigma_{00}^-}{\sigma_0}
\]

Unpolarised cross section

\[
\sigma_0 = \frac{1}{2} (\sigma_{++}^+ + \sigma_{00}^-) + \epsilon \sigma_{00}^+ = \sigma_L + \epsilon \sigma_T
\]
Effect known since early photoproduction experiments

At COMPASS kinematics:
- small for $\rho^0$ production
- sizable for $\omega$ production

Unnatural parity exchange process
→ impact on helicity-dependent observables

Crucial for description of SDMEs for excl. $\omega$ production

Sign of $\pi\omega$ form factor not resolved from SDMEs data
→ azimuthal asymmetries more sensitive
COMPASS experiment at CERN – setup with transversely polarized target

μ⁺ beam from the SPS accelerator

- luminosity: $5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
- energy: 160 GeV
- polarization: $\approx 80\%$ $\approx 50\%$

μ Filter

ECal & HCal

SM2

RICH

SM1

Microwave reversal every week

+ ~300 tracking detector planes (high redundancy)

Two 30cm and one 60 cm long target cells [two 60cm long cells in 2002-2004] with opposite polarization

- material: $\text{NH}_3$ (protons) [^6LiD (deuterons)]
- polarization: $\approx 90\%$ $\approx 50\%$
- dilution factor for exclusive $\rho^0$ production: $\approx 25\%$ $\approx 44\%$

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Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

**Used data:**

2007, 2010  (transversely polarised protons)

2003, 2004  (transversely polarised deuterons)

**Topography of vertex:**

- only incoming and outgoing muon tracks
- only two hadron tracks of opposite charges

**Kinematics domain:**

- $1 \text{ (GeV/c)}^2 < Q^2 < 10 \text{ (GeV/c)}^2$
- $W > 5 \text{ GeV}$

- $0.1 < y < 0.9$
- $0.003 < x_{Bj} < 0.35$
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

**Missing energy and energy of $\rho^0$ candidate**

- Check if the proton is intact
  \[
  E_{\text{miss}} = \frac{M_x^2 - M_p^2}{2 M_p} \in (-2.5, 2.5) \text{ GeV}
  \]
  \[E_{\text{miss}} = 0 \text{ is the signature of exclusivity}
  \]
- Check if \(E_{\rho^0} > \nu_{\text{min}}\) (minimal energy of $\gamma^*$ allowed by the kinematic cuts)
  \[E_{\rho^0} > 15 \text{ GeV}\]

**Squared transverse momentum of $\rho^0$ candidate w.r.t. $\gamma^*$**

To remove coherent production off target nuclei
\[
0.05 < p_T^2 \text{ (GeV}/c)^2 \quad \text{for protons}
\]
\[
0.1 < p_T^2 \text{ (GeV}/c)^2 \quad \text{for deuterons}
\]
To suppress non-exclusive background
\[p_T^2 < 0.5 \text{ (GeV}/c)^2\]
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

**Used data:**

- 2010 (transversely polarised protons)

\[ \mu N \rightarrow \mu N \omega \rightarrow \pi^+ + \pi^- + \pi^0 + \gamma + \gamma \]

**Topology of vertex:**

- only incoming and outgoing muon tracks
- only two hadron tracks of opposite charges
- only two clusters in ECALs timely correlated with vertex and not associated to any charged particle

**Kinematics domain:**

- $1 \text{ (GeV/c)}^2 < Q^2 < 10 \text{ (GeV/c)}^2$
- $W > 5 \text{ GeV}$
- $0.1 < y < 0.9$
- $0.003 < x_{Bj} < 0.35$
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

**Missing energy and energy of $\omega$ candidate**

- Check if the proton is intact

$$E_{\text{miss}} = \frac{M_x^2 - M_p^2}{2M_p} \in (-3, 3) \text{ GeV}$$

$E_{\text{miss}} = 0$ is the signature of exclusivity

- Check if $E_\omega > \nu_{\text{min}}$ (minimal energy of $\gamma^*$ allowed by the kinematic cuts)

$$E_\omega > 15 \text{ GeV}$$

**Squared transverse momentum of $\omega$ candidate w.r.t. $\gamma^*$**

To remove coherent production off target nuclei

$$0.05 < p_T^2 \text{ (GeV/c)^2}$$

To suppress non-exclusive background

$$p_T^2 < 0.5 \text{ (GeV/c)^2}$$
Extraction of asymmetries

- $\rho^0$ analysis
- 1D (deuteron) and 2D (proton) binned maximum likelihood estimator with subtraction of background in ($\varphi$, $\varphi_S$) bins
- $\omega$ analysis
  - Unbinned maximum likelihood estimator with simultaneous fit of signal and background asymmetries

**Background rejection:**
*For each target cell and polarization state*

![Graph showing $\omega$ sample distribution]

**Shape of semi-inclusive background** from MC
*(LEPTO with COMPASS tuning + simulation of spectrometer response + reconstruction as for real data)*

MC weighted using ratio between real data and MC for wrong charge combination sample ($h^+h^+\gamma\gamma + h^-h^-\gamma\gamma$)

$$ w(E_{miss}) = \frac{N_{RD}^{h^+h^+\gamma\gamma}(E_{miss}) + N_{RD}^{h^-h^-\gamma\gamma}(E_{miss})}{N_{MC}^{h^+h^+\gamma\gamma}(E_{miss}) + N_{MC}^{h^-h^-\gamma\gamma}(E_{miss})} $$

Normalization of MC to the real data using two component fit
*Gaussian function (signal) + shape from MC (bkg)*
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

\begin{align*}
\langle x_B \rangle & \approx 0.039 \\
\langle Q^2 \rangle & \approx 2.0 \text{ (GeV}/c)^2 \\
\langle p_T^2 \rangle & \approx 0.18 \text{ (GeV}/c)^2
\end{align*}

For proton data in agreement with HERMES results.

COMPASS results with statistical errors improved by factor 3 and extended kinematic range.

For deuteron data the first measurement.

Reasonable agreement with predictions of the GPD model of Goloskokov - Kroll.

- "handbag model"
- GPDs constrained by CTEQ6 parametrization and nucleon form factors
- Power corrections due to transverse quarks momenta
- Predictions both for $\gamma^*_L$ and $\gamma^*_T$
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

→ PLB 731 (2014) 19

- Improved method of extraction (2D)
- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

\[
\langle x_B \rangle \approx 0.039 \\
\langle Q^2 \rangle \approx 2.0 \text{ (GeV/c)}^2 \\
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\]
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

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$$\langle x_B \rangle \approx 0.039$$
$$\langle Q^2 \rangle \approx 2.0 \ (GeV/c)^2$$
$$\langle p_T^2 \rangle \approx 0.18 \ (GeV/c)^2$$
Transverse target spin asymmetry for incoherent exclusive $\rho^0$ production

- All asymmetries small and compatible with predictions of GK model
- $A_{UT}^{\sin \psi_z} = -0.019 \pm 0.008 \pm 0.003$
- Indication of $H_T$ contribution → relation with transitivity at forward limit: $H_T(x, 0, 0) = h_1(x)$

$$A_{UT}^{\sin (\phi - \phi_S)} = -2 \Im \left[ m \left( M_{0-,0}^* M_{0+,0} + M_{1-,+,+}^* M_{1+,+,+} + \frac{1}{2} M_{0-,0}^* M_{0+,0} + M_{0+,+}^* M_{0-,+} \right) \right]$$

$$A_{UT}^{\sin (2 \phi - \phi_S)} = -2 \Im \left[ m \left( M_{0+,++}^* M_{0-,0} + M_{0-,++}^* M_{0+,0} \right) \right]$$

$$A_{UT}^{\sin \psi_z} = -2 \Im \left[ m \left( M_{0-,0}^* M_{0+,0} + M_{0-,++}^* M_{0+,0} \right) \right]$$

$$A_{LT}^{\cos \phi_S} = -2 \Re \left[ m \left( M_{0-,0}^* M_{0+,0} + M_{0-,++}^* M_{0+,0} \right) \right]$$

$$\langle x_B \rangle \approx 0.039$$
$$\langle Q^2 \rangle \approx 2.0 \left( \text{GeV}/c \right)^2$$
$$\langle p_T^2 \rangle \approx 0.18 \left( \text{GeV}/c \right)^2$$

**Helicity amplitudes:**
- meson helicity
- recoiled proton helicity
- virtual photon helicity
- initial proton helicity

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Transverse target spin asymmetry for incoherent exclusive $\omega$ production

New result → to be published

- Unbinned maximum likelihood method
- 5 single spin asymmetries and 3 double spin asymmetries for transversely polarized proton target

$Q^2 = 2.2$ GeV$^2$
$x_{Bj} = 0.049$
$p_T^2 = 0.17$ GeV$^2$
$W = 7.1$ GeV
Transverse target spin asymmetry for incoherent exclusive $\omega$ production

New result → to be published

GK model predictions

private communication

- dashed: positive $\pi\omega$ form factor
- solid: no pion pole
- dotted: negative $\pi\omega$ form factor
Study of exclusive meson production will be continued at COMPASS-II

- 2012 pilot + 2016, 2017 with unpolarized LH target and RPD
- > 2017 with polarized target and RPD (subject of addendum to the proposal)

Measurement of t-slope for exclusive $\rho^0$ production sensitive to transverse size of nucleon – meson system

- $Q^2$ and $\nu$ parametrization of cross section from NMC data normalized to Goloskokov and Kroll predictions
- 160 GeV muon beam
- global efficiency $\varepsilon = 10\%$
- $L = 1.2 \text{ nb}^{-1}$ (2 years of data taking)

\[
\frac{d\sigma}{dt} \sim \exp(-b|t|)
\]

\[
b(x_B) \approx \frac{1}{2} \langle r^2_x(x_B) \rangle
\]
Summary and outlook

- COMPASS is unique to probe GPDs due to covered kinematic region of intermediate $x_{Bj}$ and availability of beams of two charges and polarizations

- Exclusive meson production $\rightarrow$ complementary measurement to DVCS, flavour separation for GPDs, sensitivity to chiral-odd GPDs

- Transverse target spin asymmetries sensitive to
  - GPDs $E \ (\rightarrow$ orbital angular momentum)
  - GPDs $H_T \ (\rightarrow$ transversity)
  - pion pole $\ (\rightarrow$ production mechanism)

- can be used to constrain GPD models
- results for $\rho^0$ and $\omega$ can be used to distinguish between GPDs for $u$ and $d$ quarks

- GPD program is continued at COMPASS-II